

# Young Globular Clusters

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**Abstract.** Star formation in starbursts appears to be biased toward compact clusters, with up to 20% of all stars formed in them. Observations with *HST* show that many of these clusters have luminosities ( $-9 > M_V > -16$ ), *UBVI* colors, and half-light radii ( $R_{\text{eff}} \approx 3$  pc) consistent with their being young globular clusters (YGC). Although we know little about the long-term stability of the youngest clusters ( $< 20$  Myr), compact clusters older than  $\sim 10 t_{\text{cross}}$  (20–40 Myr) are bound gravitationally and very likely YGCs. The present review concentrates on recent progress achieved in dating such clusters and on evidence that mergers of spiral galaxies can produce relatively rich subsystems of YGCs of solar metallicity in the remnants' halos. Studies of such subsystems suggest a scenario in which second-generation globulars form from giant molecular clouds squeezed into collapse by the high-pressure environment of starbursts. These bursts, often driven by mergers, may explain ongoing cluster formation in NGC 4038/39, the young halo globulars found around protoellipticals like NGC 3921 and NGC 7252, and the subpopulations of red metal-rich globulars observed in many giant ellipticals.

## 1. Introduction

The study of star clusters in external galaxies has been greatly facilitated by the advent of the *Hubble Space Telescope* and its superb spatial resolution. It is now nearly routine to discover hundreds of new clusters in a galaxy, measure their broad-band colors, and estimate their ages from these colors under some assumption about their metallicity. As this metallicity itself is becoming measurable through multi-slit spectroscopy on 4-m to 10-m class telescopes, the age-dating of unresolved star clusters is bound to increase in accuracy over the next few years. This review concentrates on results achieved so far on *young* globular clusters (YGC), by which I mean clusters in the age range  $0 \lesssim \tau \lesssim 1$  Gyr. I also discuss some first results on globular clusters (GC) of intermediate age ( $1 \lesssim \tau \lesssim 8$  Gyr) found in elliptical galaxies and on the possible evolutionary connection between them and the YGCs observed in galactic mergers.

## 2. Galaxies with Young Globular Clusters

Highly luminous young star clusters, and specifically YGCs, have been discovered in galaxies of many different types, suggesting that clusters are a natural

byproduct of general star formation (e.g., Elmegreen & Efremov 1997). There seems to be a tendency for massive compact clusters to form preferentially in the most intense starbursts, with up to 20% of the total UV luminosity of such bursts contributed by them (Meurer et al. 1995; Ho 1997).

Table 1 is an attempt to list all galaxies in which YGCs (and some intermediate-age GCs) have been observed in detail. Among the 34 galaxies there are 12 ongoing mergers and merger remnants that have experienced major starbursts, another dozen starburst galaxies where the bursts' cause remains unknown, and a sprinkle of galaxies that include four Local-Group members, a blue compact dwarf, and several barred spirals with circumnuclear rings of star formation.

A crucial issue concerning the youngest star clusters is their exact nature: Are they gravitationally bound and will they survive as GCs, or are they merely compact OB associations that will disperse over the next 10–20 Myr? The distinction is often difficult to make in starburst and barred galaxies with ongoing cluster formation, but becomes relatively easy in advanced mergers and remnants: Here the mean cluster ages often exceed 40 Myr or  $\sim 10 t_{\text{cross}}$ , and the case for gravitationally bound YGCs is strong (§3). Several of the galaxies discussed below are such advanced mergers. Mergers have the added advantage that they can be arranged into some sort of evolutionary sequence, ranging from early disk–disk mergers like NGC 4038/39 through recent remnants like NGC 3921 and NGC 7252 (Toomre & Toomre 1972) to suspected old remnants like NGC 5018 and NGC 3610 (Schweizer & Seitzer 1992).

Observations of young star clusters in NGC 4038/39, the prototypical pair of colliding spirals, illustrate the recent progress made with *HST*. Whereas ground-based observations showed some two dozen bright knots of intense star formation (Rubin et al. 1970), images obtained with *HST* before refurbishment displayed  $\sim 700$  young clusters (Whitmore & Schweizer 1995), and images obtained since refurbishment now reveal 14,000 point-like sources (Whitmore et al. 1999). Of these sources,  $>1000$  are likely star clusters, at least 40% ( $\gtrsim 5600$  sources) are likely individual stars, and the remainder are probably a mixture of individual stars, multiple stars, and poor clusters. Remarkably, even though this galaxy pair at 19 Mpc ( $H_0 = 75$ ) is  $\sim 30\%$  more distant than the Virgo cluster, three different populations of GCs can now be distinguished in it: 0–100 Myr old clusters formed during the present collision, a distinct group of  $\sim 500$  Myr old GCs presumably formed during a previous collision, and over a dozen truly old ( $\gtrsim 10$  Gyr) GCs that must have belonged to the halos of the input spirals.

Significant populations of YGCs have also been discovered in the two recent merger remnants NGC 3921 and 7252. In the former, *HST* images obtained with WFPC2 show 102 candidate GCs plus 49 looser associations. Most detected globulars are young (250–750 Myr), and roughly half occur in a central region of  $\sim 5$  kpc radius (Schweizer et al. 1996). In NGC 7252, deep images obtained with WFPC2 now reveal 500 candidate clusters brighter than  $V = 26$  (Miller et al. 1997). Of these, nearly 3/4 appear to be YGCs ( $\tau \approx 400$ –600 Myr) of remarkably uniform color  $V - I \approx 0.65$ , about 20% are likely old GCs ( $V - I \approx 0.95$ ), and a few dozen are very young clusters or OB associations just born in the central molecular-gas disk.

Among other colliding and merging galaxies with YGCs listed in Table 1 are the “Cartwheel” ring galaxy and the well-known peculiar cD galaxy NGC 1275 (see refs. in table, where “*Sp.*” indicates spectroscopic studies of YGCs).

### 3. The Nature of Clusters: Young Globulars

There is much evidence that the majority of bright clusters in ongoing mergers and recent remnants are young, and that many probably have masses similar to those of classical old GCs. Their youth is indicated by blue colors, high luminosities, and sometimes their location in H II regions. Masses can be estimated from the measured color indices and luminosities via comparisons with model star clusters and under the assumption that the stellar IMF in the clusters is normal. For an assumed Salpeter IMF, estimated masses typically lie in the range  $10^5 - 10^7 M_\odot$ . For two 10–20 Myr old clusters in starburst galaxies, dynamical masses have been estimated directly from measured velocity dispersions and are  $8 \times 10^4 M_\odot$  and  $3.3 \times 10^5 M_\odot$ , respectively (Ho & Filippenko 1996), in good agreement with the median mass of  $1.5 \times 10^5 M_\odot$  for Milky Way GCs.

However, to demonstrate that a young star cluster is a globular one needs to know both its size and age. As mentioned above, only if the cluster is  $\gtrsim 10 t_{\text{cross}}$  ( $\approx 20 - 40$  Myr) old and still as compact as an old GC can one conclude that it is gravitationally bound. There is now strong evidence that most bright, 40–1000 Myr old clusters in merger galaxies have half-light radii comparable to those of Milky Way GCs (median  $R_{\text{eff}} = 3$  pc). For clusters in the most distant studied mergers (NGC 1275, 3921, and 7252), only upper limits can be placed on the median  $R_{\text{eff}}$ , but since the repair of *HST* even these upper limits have been reduced to 4–6 pc. In nine nearby starburst galaxies the median radii of clusters measured with the Faint Object Camera in the UV, where *HST*’s resolution is best, are  $R_{\text{eff}} \approx 3$  pc (Meurer et al. 1995). Hence, the young clusters in these merger and starburst galaxies have similar sizes as Milky Way GCs.

For more than half of the “MERGERS” listed in Table 1 (beginning with NGC 3921), the broad-band colors of star clusters measured with *HST* yield ages of typically at least a few 100 Myr, corresponding to  $\gtrsim 10^2$  cluster-core crossing times. For 12 clusters, these ages have been verified by spectroscopic observations (§4). Thus, in connection with their small measured  $R_{\text{eff}}$  it seems likely that most of the observed clusters are true YGCs (see refs. of Table 1).

For the ongoing “MERGERS” of Table 1 (first five objects), the situation is less clear. Not all their clusters are as compact as GCs, and of those that are many are too young for us to ascertain their future cohesion. Yet, some clusters appear so enormously massive and compact that, despite their extreme youth ( $\lesssim 20$  Myr), they seem good prospects for being GCs. A good case is Knot S in NGC 4038, imaged with WFPC2 on the PC chip (Whitmore et al. 1999). This cluster is highly luminous ( $M_V = -16$ ), 7 Myr old, and has a power-law envelope that shows hundreds of individual stars and extends to  $R \gtrsim 450$  pc, making it a super star cluster of some sort. Yet, its core is very compact. The same is true to a lesser extent for its companion Cluster #430, while the  $\sim 500$  Myr old Cluster #225 shows both a softer core and a distinct radial cutoff to its envelope. These three clusters are all likely YGCs and may form an evolutionary sequence that illustrates the ongoing erosion of cluster envelopes through tidal forces.

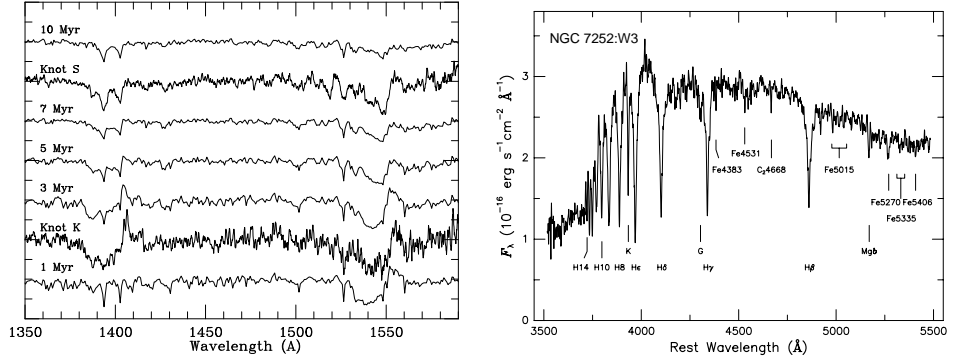


Figure 1. Cluster spectra used for age dating: (a) Knots K and S in NGC 4038 compared to model-cluster spectra (Whitmore et al. 1999); (b) Cluster W3 in NGC 7252 (Schweizer & Seitzer 1998).

#### 4. Age Dating Young and Intermediate-Age Globulars

Although approximate ages can be estimated for hundreds of clusters from broad-band (e.g., *UBVI*) images of the host galaxies, significantly more accurate ages can be obtained when individual cluster spectra are available. Figure 1 shows UV spectra of two  $<10$  Myr old clusters in NGC 4038 and a UV–visual spectrum of the  $540 \pm 30$  Myr old cluster NGC 7252:W3.

For extremely young clusters like Knots K and S in NGC 4038, the space ultraviolet is the wavelength region of choice for age dating. The UV spectra of these two clusters (Fig. 1a, *thick lines*), obtained with *HST* and the Goddard High-Resolution Spectrograph (GHRS), feature strong stellar-wind lines of Si IV at  $\lambda 1400$  and C IV at  $\lambda 1550$ . As the comparison with model cluster spectra (*thin lines*) shows, the P Cygni-type profiles of these lines in Knot K yield a cluster age of  $3 \pm 1$  Myr, while the pure absorption-line profiles in Knot S yield an age of  $7 \pm 1$  Myr (Whitmore et al. 1999). Both clusters have UV luminosities of  $L_{1500} = 4.4 \times 10^{38} \text{ erg s}^{-1} \text{ Å}^{-1}$ , which is an order of magnitude higher than the  $L_{1500}$  of R136 in 30 Dor, but still an order of magnitude lower than that of the most luminous clusters known in extreme starburst galaxies.

For young clusters in the 30–1000 Myr age range, the strong Balmer absorption lines from stars that dominate the main-sequence turnoff are a sensitive, though double-valued age indicator. Hence, additional lines like, e.g., the Ca II K line are needed to resolve the age ambiguity. Figure 1b shows a spectrum of Cluster NGC 7252:W3 featuring the prominent K and Balmer lines plus various Fe and Mg lines. Figure 2 illustrates the derivation of ages from the Balmer and K lines for seven YGCs in NGC 7252. The curves illustrate the evolution of line ratios and equivalent widths with age for model clusters of solar metallicity  $Z_\odot$  (Bruzual & Charlot 1996 [BC96]), while the horizontal lines mark values measured for the YGCs. For clusters W3, W6, and W30, the ages derived from the line ratio  $K/(H\epsilon+H8)$  are nearly identical and agree with the higher of the two possible Balmer-line ages. If the same is true for the clusters without K-line measurements, then at least six—and perhaps all seven—YGCs formed 600–400 Myr ago, shortly after the onset of the merger (Schweizer & Seitzer 1998).

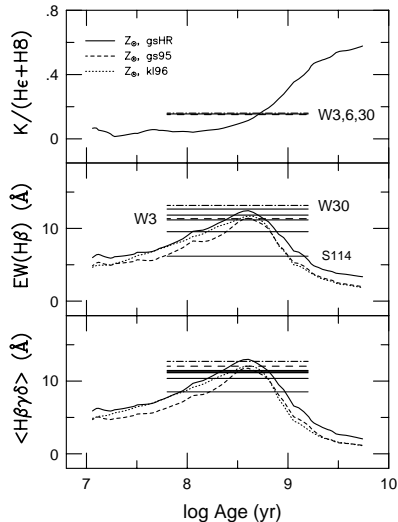


Figure 2. Evolution of line ratio  $K/(H\epsilon+H8)$  and equivalent widths  $EW(H\beta)$  and  $\langle H\beta\gamma\delta \rangle$  in model-cluster spectra with age (*curves*, computed from BC96 models), compared with values measured for seven YGCs in NGC 7252 (*horizontal lines*). For details, see Schweizer & Seitzer (1998).

For the NGC 7252 clusters W3 and W6 the available spectra have sufficiently high S/N ratios to permit a combined age–metallicity determination. Figure 3 shows two versions of the classical  $H\beta$ –[MgFe] diagram, where the Lick index  $H\beta$  is sensitive mainly to age and the combined index [MgFe] to metallicity (González 1993). The *left* version shows the data points for the two clusters superposed on a grid of isochrones (*solid* lines) and isoferes (lines of constant metallicity, *dotted*) computed from cluster-evolution models by Bressan et al. (1996), while the *right* version shows the same, but for models by BC96. According to the Bressan et al. models the two clusters have solar metallicity to within  $\pm 0.15$  dex, while according to the BC96 models they have  $\sim 2Z_{\odot}$ . Interestingly, the two model families yield very similar Fe abundances from individual line-strength indices, but a sharply different Mg abundance from  $Mgb$ . It remains unclear whether this difference reflects model uncertainties or an outright error in one set of tabulated  $Mgb$  indices.

This spectroscopic dating confirms previous cluster-age estimates based on  $UBVI$  colors and leads to the remarkable conclusion that *NGC 7252 possesses a halo population of several hundred YGCs of solar metallicity*. These clusters have a line-of-sight velocity dispersion of  $140 \pm 35$  km s $^{-1}$ , comparable to that of the globulars in NGC 5128. Thus, in NGC 7252 we witness the recent formation of a subsystem of metal-rich halo GCs.

There are reasons to believe that the metal-rich GCs in elliptical galaxies with bimodal cluster-color distributions formed during similar, though more ancient disk–disk mergers (Ashman & Zepf 1992, 1998; Schweizer 1987, 1997). Model simulations show that, as the initially very blue, second-generation metal-rich globulars age, they become similar in  $V-I$  color to the old metal-poor GCs at an age of 1–2 Gyr and then turn distinctly redder. If these simulations represent reality, we should find ellipticals with intermediate-age GCs that are slightly redder, but still brighter than the old GCs. A tentative first example is NGC 3610 (E5), where the slightly overluminous red globulars indicate an age of  $\sim 4$  Gyr if of solar metallicity, or of 6–7 Gyr if  $Z \approx 0.4Z_{\odot}$  (Whitmore et al. 1997).

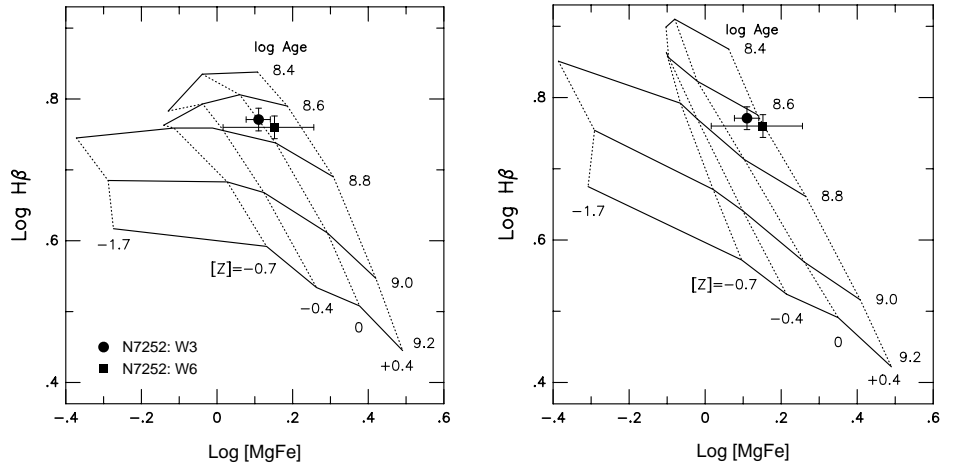


Figure 3.  $H\beta$ - $[MgFe]$  diagrams for two YGCs; isochrone/isofer grids are based on (*left*) Bressan et al. (1996) and (*right*) BC96 models.

The former cluster age agrees with the merger age estimated for NGC 3610 from *UBV* colors (Schweizer & Seitzer 1992). Spectra of the red globulars have just recently been obtained with Keck and LRIS to measure the metallicities and thus help refine the cluster-age estimates. Good other candidate ellipticals with intermediate-age globulars are NGC 5018 and NGC 1316 (see refs. in Table 1).

## 5. Evolution of GC Subsystems Formed in Mergers

Intercomparisons of the color distributions and luminosity functions of GCs in ongoing mergers, merger remnants, and elliptical galaxies strongly suggest an evolutionary sequence from young to old metal-rich GC subsystems (Schweizer 1997, esp. Figs. 1 & 2; Whitmore 1999, Figs. 2 & 3). These subsystems of second-generation clusters appear to be independent from, and additional to, the well-known systems of old metal-poor GCs (e.g., Milky Way).

Whereas old metal-poor GCs have many properties that seem to mark them as first-generation objects formed very early in the Universe's history, their genesis is understood less well than that of the second-generation clusters. Hence, understanding the latter may teach us about the formation of the former.

There is growing evidence that the second-generation metal-rich clusters formed from giant molecular clouds (GMC) embedded in the gaseous disks of spiral galaxies that merged. First, the mass functions of GMCs and the luminosity functions of young clusters are power laws with similar exponents:  $N(\text{GMC}) \propto M^{-1.6}$  and  $N(\text{GC}) \propto L^{-1.6 \text{ to } -2}$  (Harris & Pudritz 1994). Second, even the mass ranges of GMCs and globulars are similar:  $\sim 10^5 - 8 \times 10^6 M_\odot$  and  $10^5 - 5 \times 10^6 M_\odot$ , respectively, for Local Group galaxies. And third, in the merger remnants NGC 3921 and NGC 7252 the YGCs are distributed radially exactly like the stars ( $r^{1/4}$  law), showing that the progenitors of the YGCs experienced the same violent relaxation as did the average star (Schweizer et al. 1996; Miller et al. 1997). This implies that the YGCs formed from pre-existing compact progenitors, rather than from instabilities developing in gas accumulated by the

mergers at the remnants' centers. The only compact progenitors of sufficient mass that we know of are the GMCs of the merging spirals.

Interestingly, Jog & Solomon (1992) predicted that the rapidly rising pressure of a starburst-heated interstellar medium would squeeze any embedded GMC into collapse and extremely efficient ( $\sim 50\%$ ) star formation, leading to the formation of massive compact star clusters. Such a high efficiency seems to agree with the observed mass ranges of GMCs and globulars mentioned above. If so, this merger- and starburst-induced squeezing is occurring full-scale in NGC 4038/39 and NGC 3256, has diminished to a trickle in NGC 3921 and NGC 7252, and is past history in dynamically young ellipticals like NGC 3610. As we improve the spectrophotometric dating of globular clusters from their integrated light, we can hope to refine this still sketchy scenario and perhaps extend it to ellipticals as old as those formed in clusters like Virgo and Coma.

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Table 1. Galaxies With Young Globular Clusters.

Galaxy	References
MERGERS	
NGC 4038/39 (Antennae)	Whitmore & Schweizer 95; Whitmore+ 99
NGC 3256	Zepf+ 99
NGC 7727	Crabtree & Smecker-Hane 94
NGC 6052	Holtzman+ 96
A0035-335 (Cartwheel)	Borne+ 97
NGC 3921	Schweizer+ 96
NGC 7252	Schweizer 82; Whitmore+ 93; Miller+ 97; <i>Sp</i> : Schw. & Seitzer 93, 98
NGC 1275	Holtzman+ 92; Carlson+ 98; <i>Sp</i> : Zepf+ 95; Brodie+ 98
NGC 3597	Lutz 91; Holtzman+ 96
NGC 5018	Hilker & Kissler-Patig 96
NGC 1316	Schweizer 80; Shaya+ 96; Grillmair+ 99
NGC 3610	Whitmore+ 97
STARBURSTS	
NGC 253	Watson+ 96
NGC 1140	Hunter+ 94
NGC 1569	Arp & Sandage 85; O'Connell+ 94; De Marchi+ 97; <i>Sp</i> : Ho & Filippenko 96a
NGC 1705	Meurer+ 92, 95; O'Connell+ 94; <i>Sp</i> : Ho & Filippenko 96b
NGC 1808	Tacconi-Garman+ 96
NGC 3034 = M82	van den Bergh 71; O'Connell & Mangano 78; O'Connell+ 95; Gallagher & Smith 99
NGC 3310	Meurer+ 95
NGC 3690	Meurer+ 95
NGC 3991	Meurer+ 95
NGC 4670	Meurer+ 95
NGC 5253	van den Bergh 80; Caldwell & Phillips 89; Meurer+ 95; Calzetti+ 97
NGC 7552	Meurer+ 95
OTHER GALAXIES	
LMC, SMC, M33, M31	Most major Local Group galaxies; many references
He 2-10	Blue compact dwarf galaxies; e.g., Conti & Vacca 94
NGC 1019, NGC 1097, NGC 6951, NGC 7469	Barred galaxies, circumnuclear rings; e.g., Barth+ 95; Ho 97

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